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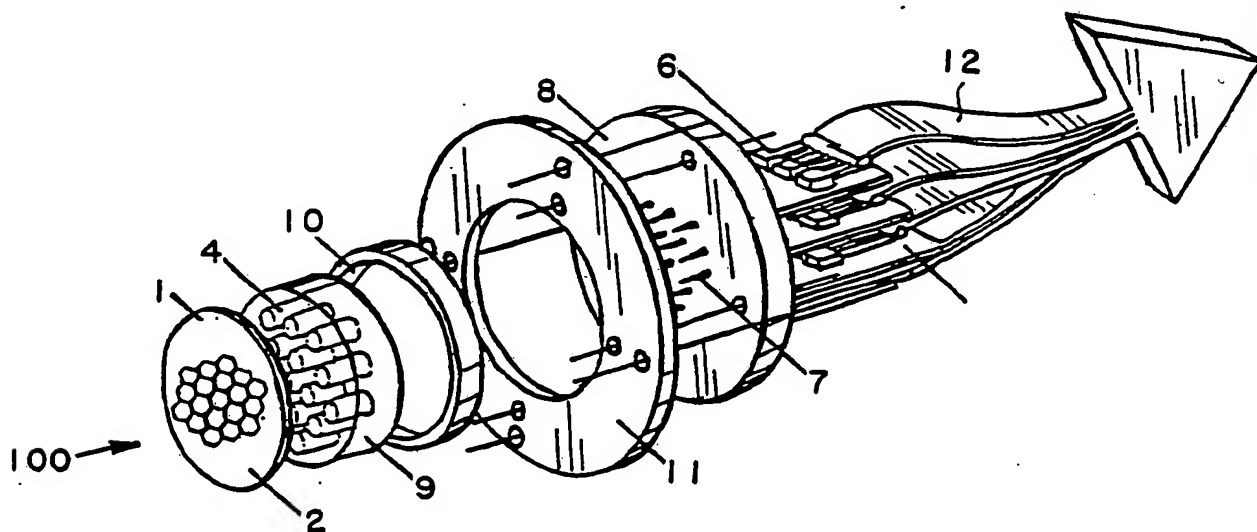
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(54) Title: CAPACITOR ARRAY SENSORS TACTILE AND PROXIMITY SENSING AND METHODS OF USE THEREOF

(57) Abstract

Multiple capacitor arrays which are employed for a diversity of applications, particularly in the field of robotics. The capacitance sensor array is used for proximity and tactile sensing of properties of an object and comprises a plurality of capacitor plate elements formed in a predetermined array, means for actively connecting each capacitor plate element and the object to one of a plurality of oscillating circuits so that the oscillation frequency of each of the oscillating circuit is a function of the capacitance between each capacitor plate element and the object, and means for generating an output from the sensor which is a function of the tactile properties of the object from the plurality of oscillator circuits.

CAPACITOR ARRAY SENSORS
TACTILE AND PROXIMITY SENSING
AND METHODS OF USE THEREOF

BACKGROUND OF THE INVENTION

5   In the past there have been a number of uses of capacitance based sensors, typified by the use of metal plated onto mylar film employed as one plate of a capacitor for the evaluation and quantification of surface roughness and the like of machined metal surfaces 10 and the like.

Such sensors have established a highly useful role in industrial manufacturing and in the machine tool industry, in particular, for the characterization of surface properties. As the art is now aware, these 15 sensors are bases on the employment of the variable capacitance, due to the coupling of the sensor with a surface to be evaluated, by techniques such as controlling the rate of an oscillator circuit, so that the frequency of the oscillator is directly determined 20 and altered as a function of surface roughness.

The need for improved tactile sensing systems has dramatically increased as "intelligent" machines and robots are finding greater usage in sophisticated tasks, such as robotic assembly and the like. Tactile sensing 25 needs include the detection of slip, or incipient

slipping, for robotic grippers or "hands" and related tools, the identification of shape, surface features, texture, gripping force, and related factors.   Existing applications attempt to substitute non-tactile techniques

5   for these functions, and robotic implements generally lack effective tactile sensing at the gripper to provide adequate control information to govern motion and operation of the robotic tools.   It has generally been considered necessary to rely on optical robot vision

10   techniques, and other highly complex operations to make up for the lack of direct, high speed tactile feedback information.

Tactile sensing is generally defined as continuous variable sensing of contact conditions over an area, as

15   distinguished from simpler "touch sensing" which is usually associated with force or torque measurements. Tactile sensing includes the abilities of "groping", and in so doing, of identifying shape, surface features, texture, force and slip. By one means or another, one or

20   more of these features and capabilities are required in virtually all automated and robotic applications.   These needs are not always adequately met by existing techniques.   It has been estimated, for example, that at least fifty percent of all robotic applications need slip

25   detection to provide feedback control signals for the governance of gripping force, but the techniques

presently available are too slow, too insensitive, and too complex and expensive to be adequate to meet the existing need. The need of the art is expected to grow, both in magnitude and in the level of performance, in the

5   near future.

In an entirely different aspect of robot technology, the techniques for guiding motion of robotic implements and tools is dependent on non-contact, non-tactile sensing. These requirements impose a completely

10 different set of problems for the art, and here too there are serious limitations.

In the simplest systems, the robots are "blind," and movement is through a predetermined pattern of movement and function based on memory. While such operations are

15 suitable and even highly effective for many types of operation, the burdens on the support and logistics are critical, expensive, and limiting on the power and particularly the flexibility of the system. Parts must be fed to precise location, in precise orientation, and

20 must be assuredly within tolerances. Even slight deviations will disrupt the effectiveness of the operation.

In order to overcome these limitations, and to provide greater flexibility and more lenient tolerances,

25 remote sensor computer vision based controls have been developed extensively. Such optical, and related systems

are generally effective, but only at the expense of considerable time and computational complexity which lead to relatively slow operations, high capital costs, and difficulties in the areas of greatest concern, the final
5   approach guidance to contact between the robot gripper or implement and the part. Failures are common in such system because of the difficulties of real time resolution of ambiguities of shape recognition and in the lack of adequate resolution of the remote sensors at
10   final approach. As the "hand" approaches a part to be "picked up," the need for high resolution is greatest, but the capabilities of such systems is deteriorating because of obscured vision at the critical point, and by virtue of the decrease in relative resolution as the
15   parameters requiring control converge. The capabilities of such systems are inherently the reverse of what is required; as the approach becomes more demanding, the nature of the systems results in deteriorating sensitivity and resolution. Proximity sensing and real
20   time control remains a pressing need in the art. In addition, if computer vision systems are relieved from the fine detail resolution requirements of final approach guidance and control, they can be made faster and more effective in gross motion control and guidance, collision
25   avoidance, and related control functions to which they are more directly suited.

It is accordingly an object of the present invention to provide proximity and tactile sensors which will meet the needs of the art in the foregoing and other respects.

SUMMARY OF THE INVENTION

5   In the present invention, multiple capacitor arrays are provided which are employed for a diversity of applications, particularly in the field of robotics, which are great improvements in the techniques employed in the past.

DESCRIPTION OF THE DRAWINGS

10   Figure 1 is a drawing of the sensor elements of the array shown in exploded, scematic form;

Figure 2 is a stylized drawing of the electrical circuit elements of the sensor and their function;

15   Figure 3 is a drawing of a preferred arrangement of the sensor elements of the array; and

Figure 4 is an exploded representation of the structure of a preferred specific embodiment representing the best mode to date of the array of sensor elements

20   shown in Figure 3.

DESCRIPTION OF THE INVENTION

The multiple element arrays are configured for both collective and separate sensing of capacitance properties, permitting a variety of non-contact and

25   contact based measurements, from which a number of important determinations can be made. These include

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measures of approach and proximity, which can be employed as a real time machine control parameter for the direction of robotic tools for engaging and manipulating objects, for the determination of object location,

5 orientation, and configuration, including such diverse matters as shape, edge location, part identification, measurement of size and shape of parts for the detection of defects, measure of surface properties, including surface roughness, conformity to quality control

10 tolerances for shape, dimensions, surface finish, and the like, and for the detection of slip, and particularly incipient slip, of a part relative to a sensor when used as an element of a part holder in robotic implements such as robotic "hands" and the like, for real time grip

15 feedback and control systems. The capacitance array based detectors and sensors of the present invention operate in a highly sensitive and high speed manner suitable for real time control of robotic equipment and elements via analog or digital electronic control

20 techniques. Digital systems, based on closed loop feedback control techniques are preferred, particularly with discrete multiplexing of capacitance measurement from each capacitor plate in the array. Serial polling may also be employed, although the sampling rates

25 required for some uses of the system will limit the desirability of such techniques.

In the present invention, the features and functions
are attained by forming an array of a plurality of
discrete capacitor plates on a surface. Each individual
capacitor plate will conform generally to the structure

5   of the sensors of the prior patents of Risko and of Shum,
disclosed above. In providing a plurality of such
elements, there are requirements for providing separate
leads for each, and when the elements are formed, as is
preferred, from metal plated Mylar film, the multiple

10 elements and the associated leads therefor can be readily
made by the same techniques described in the prior
patents for the formation of individual elements. The
layout is not critical, but it is preferred that it be a
regular repeating pattern, formed with a high degree of

15 precision, since the accuracy of the measurements to be
taken will depend on the accuracy of the pattern.
Otherwise it may be necessary to employ time consuming
and difficult error compensation techniques in the
evaluation of the output from the sensors. Layout of the

20 array is preferably in a hexagonal pattern of hexagonal
elements, but other arrangements are effective as well.

Resolution of the measurements to be taken with the
system based on evaluation of the capacitance values for
each element or cell in the array will be dependent on

25 the size of the elements, while other evaluations will be
based on comparative values taken from a plurality of

elements, and the resolution will be dependent on the closeness of the elements as well as the discrete size of each.   Other parameters, which treat the discrete elements collectively, as a single capacitor plate, are

5 dependent on the size and, more particularly, the total area of the array as a whole.

In this context, then, it is self evident that the number of elements, their size, and the closeness of their packing should be consistent with the values to be

10 determined and the resolution required, as will be developed in more detail hereinafter.   As a general parameter, the number, size, packing density, and total area of the elements of the array should be as great as the capacity of the control system employed will accept

15 at speeds consistent within real time feedback rate requirements.   Some of the parameters of interest in the present system require sensing and data evaluation at relatively high speeds, compared to prior art usages of such sensors as single elements.   For example, for slip

20 sensing applications, the sampling rate should be at least about 300 Hertz, and preferably 1,200 Hertz, or even higher.   Since the data from a multiplicity of elements in an array are required, the computational load on the control system may be quite demanding.

25

Each of the measurable or detectable parameters which is to be derived from the sensor array is dependent on a different set of criteria and must be considered individually. Thus, it is not possible to employ the

5   sensor as a proximity detector and approach control input by the same techniques and algorithms employed for slip sensing. Nonetheless, it is important to recognize that the present invention is predicated on the ability of a single sensor array to adequately and effectively perform

10   functions which have not been available to the art at all, as well as others which have not been well handled by prior art approaches in real time contexts. It is an added benefit that the array sensors will also function in other contexts and for other purposes previously known

15   for single element sensors with no diminution of effectiveness.

Proximity sensing is a function of the high level of sensitivity of capacitance as an inverse of the distance between capacitor plates. If the sensor of the present

20   invention approaches an object which, by the techniques discussed hereinafter, acts as an opposed capacitor plate in relation to the array as a whole, changes in capacitance becomes detectable at substantial distances, measurable in pluralities of inches in many cases, and

25   becomes progressively more sensitive to changes in distance as the absolute distance grows smaller. Thus,

by evaluating the capacitive coupling between an object and the sensor array, with the array carried on a robotic "hand" or gripping tool for example, as the relative distance decreases, the capacitance change is a function

5   of the distance between the two, and the values obtained can be employed in a closed loop feed back control system to direct the approach to the object and engagement therewith with very high precision and accuracy. For a given element, the results are very highly reproducible,

10 so that a very safe and effective control of such operations is achieved. Unlike optical systems, the resolution of the present system increases as the distance remaining before contact becomes smaller, so that the closer the approach, the closer the control

15 which becomes possible. At greater distances, where only coarse control is required, the lack of sensitivity is of little importance, and it may be desirable to use other techniques for gross motion control and collision avoidance, for example.

20   As those of ordinary skill in the art will readily recognize, it is relatively simple to combine the values of the discrete elements of the array of the present invention into a single composite measure of the capacitance between the array and the sensed object. The

25 capacitive coupling involved may be direct coupling of the sensor array to the object, or an indirect coupling

based on the interference of the object with the capacitive coupling of the sensor array with a background capacitive element. In either case, the coupling value is best treated as a single value, with the array treated

5   as a single capacitor plate.

As contact occurs, the proximity regime will have performed its control function, i.e., of guiding, slowing and limiting the approach mechanism, and initiating the engagement element, such as a robotic gripper or "hand"

10   or the like. At this point, the collective function will have served it's purpose, and the control system should thereafter switch into a different mode, based on the capacitive coupling of the discrete elements of the sensor array individually or in discrete groups of

15   elements.

Among the parameters to be evaluated, surface roughness can be measured in one or more points of the sensor contact area, in the manner disclosed by the above cited prior art.

20   Additional parameters to be measured and determined may include the following: Shape; orientation of shape; part identification; edge location; critical parameter tolerances; and slip of the contact between the array and the part. Each of these is of great importance in the

25   field of robotics and computer aided manufacture, and there is a rather great body of prior art relating to

each such function. It is a great advantage of the present invention that each of these diverse functions can be effectively performed by a single, relatively simple sensor, with a high degree of accuracy and

5   reproducibility. The prior art has grave difficulties with each of these functions, and some are not available in the prior art in any effective way at all.

The determination of shape by the array is developed by polling of the discrete elements of the array to

10   arrive at a capacitive coupling pattern which, either via proximity determinations or contact characteristics or some combination of both, will provide a "profile" characteristic of the shape of the part. By comparison of the profile of a part with a library of such profiles,

15   via a lookup table or the like, the general shape properties of the object, or some component part thereof, can be ascertained. The capacity of the system for direct determination in the foregoing fashion may be sufficient in many circumstances to determine the

20   identification of one among a relatively limited inventory of possible objects. In other circumstances, the direct profile measure may result in ambiguities, and require further discrimination. The additional discrimination is a feature of the discussion

25   hereinafter.

Part orientation is closely related to part
identification, and poses like requirements, although
there are enough differences to impose some additional
and different requirements. Both in the proximity
5   sensing phase of operation, and in the groping which
occurs at the point of initial contact, a number of
parameters can be evaluated which in many circumstances
will be adequate to both identify the part and define its
orientation. Among these, the coupling profile on
10   approach will be characteristic of orientation as well as
shape, for any part which has features which affect the
coupling profile. Substantially any feature will have an
influence on the capacitive coupling characteristics.
There will be other part identifying information in the
15   surface roughness characteristics described above. It is
also possible to evaluate the properties of shape of an
edge or other feature which contacts the sensor array by
triangulation of values obtained by individual sensor
elements within the array. Via the capacitive edge
20   effects, the presence of nearby features can be
determined. Through the well known technique of lookup
tables, or some equivalent approach to pattern
recognition, the orientation of the part and its
identification can be made in all but the most highly
25   ambiguous of cases.

The techniques of pattern recognition are well known in the art and do not in themselves form a part of the present invention. The advantage of the present system lies in the multiplicity of independent parameters

5   available to the recognition system, and the resulting facility with which unambiguous determinations can be made. The same characteristics can be highly effective in reducing the scope of the search and, in turn, result in greater speed of reaching decision points and reduced

10 computational burden. Unlike computer vision based pattern recognition techniques where the available data is all of a like kind, based solely on size and shape parameters, the divergent properties evaluated in the present system afford a simpler decision making logic.

15 If the present system is coupled with an optical or related pattern recognition system, which may be desirable for other purposes as noted above, the computational demands on the optical system are reduced, and lower resolution can be employed, since the decision

20 making ambiguity can be performed by other means. Even relatively crude and rough pattern recognition results can be quite effective when supplemented with the very different perceptions available from the present system.

Quality control evaluation of parts to assure that

25 each part is within acceptable tolerances is another aspect of the present sensor array, or in some cases

another dedicated array for the evaluation of a specific part. In this aspect, the objective is to quantify the appropriate dimensions, surface finish, and other related characteristics of a part in relation to a set of

5   tolerances. For simple parts, the data available from the sensor array as described above may be adequate to the need. It may be, however, that more detailed data, or more sensitivity is needed than can be attained with the primary sensor array. In that event, a secondary

10   sensor array, specific to the part to be evaluated, will be provided.

The part specific sensor will be of a shape and size closely · corresponding to the surface of the part, and through proximity and tactile sensing, as described

15   above, conformity to the required shape and dimensions can be rapidly and precisely determined. The secondary sensor array is discussed in more detail infra.

Once a robotic gripper has successfully navigated to a part, identified the part and its orientation and

20   successfully engaged it, it must be manipulated by the robotic system. In that context, picking up the part, moving it to an intended location, and utilizing it in the intended manner, requires several additional controls. The system must have a reliable means to

25   insure the integrity of the grip so that the part is not damaged by excessive force or dropped by insufficient

force.   At a more subtle level, slip sensing is of
considerable importance in assuring proper assembly
operations, particularly in stopping the operation when
something goes amiss, such as a misfit of parts, or the
5   like.   The avoidance of slip at proper gripping and
assembly forces is a direct assurance of proper assembly,
alignment, and fit, thus affording a direct quality
control and assurance parameter of considerable value in
relation to the finished assembly, as well as furnishing
10   substantive information for control feedback in the
manufacture of the component parts.

        Slip sensing in the present invention is based on
the observation that discrete areas of surfaces of parts
vary in surface roughness. In even the most uniformly
15   controlled industrial processes, the finish of the
surface of a part will vary by at least about ten
percent.   Thus, it has been observed that when a
capacitance sensor of the type disclosed herein is
engaged with a surface, any slip between the sensor and
20   the surface will result in a directly detectable change
in the capacitance and will be a highly reliable
indicator of such slip.   It has been found that the
sensitivity of the detection is adequate to detect a
motion of one microinch (1.0×10^{-6} inches), although it
25   will be sufficient in most applications to detect a
motion on the order of 50 to 100 microinches, thus

simplifying the system. The response time for such a measurement is a function of the sampling rate and cycle time of the measurements, which are preferably over a period of ten milliseconds or less. The sensitivity and

5 response of the system can be enhanced by the employment of higher sampling rates and higher base rates of the counter oscillator whose rate is altered by the variable capacitive coupling between the sensor and the part. At these levels of sensitivity, an effective real time

10 closed loop feed back data source is generated which can be effectively and reliably employed to control gripping force, in a fashion never before available to the art.

All the operations in the present invention are based on the primary relationship

15 $$C = K \times A/t$$

where C is capacitance, K is the effective dielectric constant (a composite value in the present context), A is the area of the coupling surfaces, and t is the average distance between the plates.

20 In the context of the present invention, K and A are effectively fixed values, so that in the proximity based measurements, C is seen to be inversely proportional to t. It is also apparent that as t grows smaller and smaller, the magnitude of the change on C grows larger

25 and larger, so that at the stage of close approach, even very small and gradual changes in distance produce quite

substantial signals for control purposes. The increase in sensitivity and resolution at the critical juncture has not heretofore been available to the art.

5   As contact is achieved, surface roughness can be ascertained in the manner disclosed by Shum and Risko in their respective teachings. It is important to note however, that any element of the array which is not in full contact with the surface, i.e., not in contact at all, or having an edge cross its area, will produce an

10   aberrant value, and should be disregarded. Such anomalies will be easily dealt with, however, by using only the capacitance value or values with the greatest magnitude among the plural elements.

What are anomalies for the measurement of surface

15   roughness are significant data for the evaluation of edge location and shape properties, so that the data disregarded in the roughness determination is directly used in the evaluation of edge locating and shape evaluating operations in the present system. The

20   triangulation of the varying data among the plural cells of the array is computationally simple, since the extent of coverage of each cell is the variable, while K and t are fixed values, and for each cell, C is directly proportional to A, as given in the above formula,

25   although it is necessary to correct for capacitance edge effects. With a known topology of the elements or cells

of the array, and the measured proportion of each cell which is in contact with the part, the calculation of edge location and shape characteristics are relatively simple. For any part in which the shape of such an edge

5 is unique, the shape determination is an identifying parameter. In most other circumstances, the shape determination of the edge portion in contact with the sensor array will not be a dispositive characteristic, but it will furnish some input to the decision making

10 process. In circumstances where the edge does not pass across the cells of the array, the edge is a feature of the structure, as discussed below.

While the primary coupling involved in the direct measurements with the sensor array system of the present

15 invention are based on the directly opposed areas of the cell and the part, capacitance edge effects play a direct and important role. In many of the determinations in the present invention, it is necessary to take steps to minimize edge effects to assure the greatest reliability

20 of the results. On the other hand, edge effects can be constructively employed when it is recognized that features remote from the contact area itself will influence the edge effects. While the specific consequences of a particular feature, and the nature of

25 the detectable influence on capacitance is highly complex and difficult to predict, the use of predetermined

effects, and patterns of effects, can be highly effective
in pattern recognition operations for the identification
of parts, and for the measurement of part orientation.
Most often these aspects of the system will be based on

5   known pattern recognition techniques, with prerecorded
patterns stored in a library of values used as a lookup
table.   While other approaches are possible, the
resolution of shapes, locations of features and other
such evaluations based on edge effects are

10 computationally intense and are not usually preferred.

The sensor elements of the array, considered
individually, each have a structure shown in exploded
schematic form in Figure 1.   In that Figure, the sensor
capacitor plate 1 is carried on a dielectric 2, required

15 to prevent shorting of the capacitor plate 1 to a part or
workpiece 3.   The plate 1 has electrical lead 4, which
together with part contact lead 5, constitute the input
capacitance leads to the oscillator and counter
circuitry.

20 The electrical circuit elements of the sensor and
their function in the present invention are shown in
stylized form in Figure 2.

Referring again to Figure 1, the active capacitor
plate element 1 and its dielectric 2 are preferably

25 formed from an electrical conductor, such as aluminum or
the like plated on the surface of a synthetic polymer

film, such as polyethylene terephthalate film, a cross linked polyethylene imine, or the like. Aluminum coated Mylar is commercially available and is preferred. The aluminum can be etched from the surface of the film in

5 known fashion to provide a capacitor plate element of the desired size and shape. The electrical contact from the sensor plate element 1 to the oscillator component is furnished by an electrical lead 4 which may be an integrally formed component of the etched surface, or may

10 be an electrical lead bonded to the surface of the capacitor plate element 1 with a conductive adhesive, such as silver filled epoxy resin based adhesives and the like. Solder connections may also be employed if care is taken to protect the components of the system from the

15 heat required.

In the context of the present invention, the electrical lead 4 is preferable a conductive elastomeric material, preferably a silicone elastomer with a conductive filler. It is far easier to arrange the

20 multiple contacts required for the sensors in such case than by efforts to employ the conductive layer on the Mylar film. In an alternate arrangement, the electrical lead may be formed of conductive fibers, such as X-Static silver plated nylon fiber monofilament available from

25 Sauquoit Corp. in Scranton, Pennsylvania, U.S.A.

The capacitor plate element 1 is preferably provided with an elastomeric backing 9 which serves to press the surface of the dielectric face of the sensor into a uniform and even contact with the surface of a part or
5   workpiece as an aid to the reproducibility of the measured values which are a function of the workpiece, independent of the specific applied force of the robotic gripper, the alignment angle of the sensor to the workpiece surface, and other like variables.

10   The capacitor elements as shown in Figures 1 and 2 are, as has been noted, components in an array. The preferred arrangement of the array is a hexagonal pattern of hexagonal elements, as shown in Figure 3. In Figure 3, a specific array is shown, of a multiplicity of plate
15   elements 1, on a common dielectric film, of Mylar or the like. While in Figure 3, nineteen (19) capacitor plate elements 1 are shown, other numbers of component plate elements can be employed, in other configurations, to suit particular applications.

20   As a general rule, the higher the number of elements for a given sensor area, the greater the resolution which can be achieved. As those of ordinary skill in the art will recognize, greater numbers of elements will require higher manufacturing costs, greater computational burdens
25   on the system, and greater complexity and control difficulties. It is accordingly preferred to limit the

number of elements to the minimum necessary to achieve
the required degree of resolution for a given
application. In addition, the capacitance values are a
function of plate area, and as the dimensions of the

5   individual elements is decreased, and the number is
increased, there is a limit where the noise of the system
from edge effects and ambient noise becomes a barrier to
increasing resolution. The limits on the dimensions will
vary, but as a general rule, elements having an area of

10   less than about 0.02 square millimeters are likely to
prove to have signal to noise ratios which approach the
limits of practical circuit design and real time
computational burdens. In cases of compelling need,
where the extra demands on the circuits and computing

15   loads can be justified, it is possible to achieve
meaningful results at a level which is about one order of
magnitude smaller, but the general usage of the system of
the present invention will often be satisfied without
resort to the small elements which are possible, and

20   sizes on the order of 0.1 to 2.0 square millimeters will
be effective in the majority of applications. While
there may be contexts where even coarser resolution may
be sufficient, and while there is no functional upper
limit on the size of the plate elements, it will

25   generally not be of any practical interest to make such
arrays with elements having more than about 10 or 12

square millimeters. Even in applications which do not require the resolution of such arrays, it will rarely be worthwhile to make arrays with larger plates.

5   For the array configuration shown in Figure 3, the structure of a preferred specific embodiment representing the best mode of the sensor to date is shown in exploded form in Figure 4. The reference numerals correspond to those of the proceeding figures, where 1 represents the capacitor plate elements, collected into a multiple

10   element array 100, 2 is the dielectric, 4 represents the multiple elastomeric electrical leads from each capacitor plate 1 to its associated oscillator 6. As seen in the present Figure 3, there is one oscillator for each capacitor plate. Although not all the plural leads 4 and

15   not all the oscillators 6 can be shown in the figure without a loss of clarity, it is readily apparent that the structure will benefit considerably from the microminaturization of these components. See Figure 4. The plural oscillators are preferably incorporated into a

20   single integrated circuit chip with multiple lead inputs and outputs. These matters are discussed in greater detail infra.

     The electrical leads 4, which are present in a number equal to the number of the capacitor plate

25   elements 1 in the array, are, as previously noted, formed of a conductive elastomer material, bonded to the face of

the capacitor plate elements with a conductive bond, preferably a silver filled epoxy resin adhesive. Many such adhesives are commercially available in the art. The connection between the elastomeric lead 4 and the oscillator 6 is conveniently made by contact pins 7, which may themselves be adhesively bonded to the leads 4. The contact pins 7 are carried on and penetrate through a mounting plate 8, formed of a suitable non-conductive material, e.g. nylon, polyimide, or other like polymer material. The mounting plate 8 serves as a mount for the oscillators 6, and associated circuit elements, including output leads 12, and may, if desired be a printed circuit board designed for the purposes required in the context of the present invention. The capacitor element array 100, with plural capacitor plate elements 1, and the dielectric 2 are provided with an elastomer backing 9 which performs the functions already discussed supra, and which also serves to pot the electrical leads 4, insulate them from one another, and to furnish physical support for the array of leads. The potting elastomer should have an elastic modulus which is not too greatly different from the moduli of the plural leads 4, and should preferably be about the same or slightly higher. The length of the leads 4, and the thickness of the elastomeric potting layer 9, should be the minimum necessary to connect the sensor plates 1 to the

oscillator contacts 7, and to provide the backing
necessary to maintain the contact of the array with the
surface of a workpiece in a uniform even contact
pressure. The assembly is completed by mounting ring 10,
5 which functions to confine the sensor array in place,
dimensioned so that the dielectric layer 2, and the
capacitor elements 1 stand proud of the surface by a
small amount, and upon contact with a part or workpiece
are compressed, along with the elastomeric backing 9.
10 The entire assembly is held in place in an aperture in
the surface of its robotic gripper or other environment
of use by retainer ring 11.

Output leads 12 pass the signal from each of the
oscillators 6 to the signal processing circuitry at an
15 external location not shown.

Figure 4 shows a schematic version of the circuitry
of the sensor, including the various elements of the
array which are electrically active. The reference
numbers correspond to those employed in the other figures
20 for corresponding elements.

While the present invention is directed to the
sensor, and its use in the generation of the outputs
described herein, the signal processing is of course an
important element in the use thereof. The output of each
25 oscillator in the system is the functional equivalent of
a single capacitor sensor, and may be used singly, as

disclosed and discussed by Shum and Risko, disclosed and discussed above. It is, however, when the plural output signals are used collectively that the unique benefits of the present invention are particularly achieved. It is

5   when the values of various of the elements are separately established and evaluated, and the results combined and compared in appropriate fashion, that the highly desirable proximity and tactile sensing properties are achieved.

10   For the detection of slip, first and foremost, the capacitance values of a variety of elements in the array is polled, ordinarily in serial fashion, and the oscillator rate determined for each, or more commonly some digital value which is a function of the oscillator

15   frequency, such as a count of the beat frequency of the oscillator against the clock rate of the system, or the like, is evaluated for change over time. Within some dead band zone which is desirable to damp the effects of minor variations in the system, change is ignored, so

20   that a change outside the deadband will be a direct measure of incipient slip between the workpiece and the sensor array. As those of ordinary skill in the art will readily recognize, the output can be employed in the control of gripper force, so that as incipient slip is

25   recognized in the system, the force is increased until slip ceases. As already noted, the system can detect

slip on the basis of a motion of as little as one microinch, although the provision of a deadband and a relatively slow cycle of measurement may result in a sensitivity of higher magnitudes. At a ten millisecond

5 interrogation cycle or slower, it has been found that slip can reliably be detected in one cycle. For most applications, a thirty to fifty millisecond cycle rate will be sufficient. While no actual lower limit to the sensitivity has yet been attained, it is believed that

10 the sensor is capable of detecting slip within less than one millisecond, although at that level the computational load will make such rates of limited use until better real time computation is available.

As those of ordinary skill in the art will readily

15 recognize, the signal processing requirements of the system are intense if real time utilization of the signals generated by the multiple oscillators at the high level of resolution contemplated herein. It will generally prove effective to reduce the data manipulation

20 burden by digitizing the oscillator signals. This is conveniently done by a simple count of the oscillator frequency on some appropriate time basis, or by taking the count of the beat frequency of the oscillator against some standard clock rate oscillator. Additional facility

25 can be achieved by multiplexing of the multiple channels of data. The compacted data thus attained represents a

manageable but data rich input to the data processor, which can then manipulate the signals in the various fashions described herein above. It is additionally possible to compress the data still further by polling

5 the individual elements, or sets of individual elements in serial fashion by switching among the plurality in some regular way. Thus, the output will then be a composite of discontinuous sampling of the individual elements. None of the values to be determined is

10 dependent on continuous data from any single element of the array, although it should be noted that if such techniques are employed, slip sensing and proximity sensing and approach control are very directly time dependent. If these parameters are measured, the

15 switching should be at a frequency consistent with the requirements of these time dependent features.

Specific algorithms for each of the functions is available to those of ordinary skill in the art, and will not be individually discussed herein. It will suffice

20 for the guidance of the practitioner to note that the employment of specific algorithms, particularly in pattern recognition, for the determination of identity and orientation of objects is based on a rich variety of data which can be derived from supplements to the

25 standard positional shape data to which optical systems are limited, and that the recognition system can benefit

from a reduction in computational requirements if the tactile data are employed to narrow the range of possibilities in a binary decision tree, for example, to families of possible objects, and to exclude other

5 possibilities which do not have corresponding properties. In this fashion, the discrimination of the system can be increased, and the time dependent computational load reduced. It is particularly useful to use tactile data concerning surface characteristics and edge shapes as a

10 means to exclude from shape recognition and pattern recognition computations all the objects of materials or finish properties which do not correspond to the data. If even a few possible objects can be excluded from the pattern recognition searches, material savings in

15 processor activity and search time can be realized. Obviously, such benefits will be dependent on the set of possible objects and the degree to which they can be grouped by such tactile properties. There will be a considerable opportunity to use such system logic in most

20 situations, however.

In specific quality control applications, the degree of discrimination and resolution available in the general purpose sensor array may not be be sufficient for measurement of the closest tolerances required, and it is

25 therefore desirable in such circumstances to provide additional part specific dedicated array sensors

conforming to the configuration of the part shape and size. By the use of such dedicated sensors, conformity to the required shape can be directly and precisely measured and evaluated, leading to a real time decision

5   concerning the critical quality control parameters. It is also possible to employ the specific data to define and control specific part correction processes to bring defective parts within tolerances.

The dedicated sensor array for any specific element
10 or part will be electronically the same as the primary sensor array, but the capacitor plate array and the dielectric will be formed into a shape closely corresponding to the surface of the desired part. The potting composition is employed to preserve the shape,
15 and the length of the leads may require adjustment. Otherwise the structure will be the same. It is desirable that the potting formulation be more rigid, i.e., less compressible, than in the more general case, since it is conformity to the desired shape which is to
20 be determined, and with a relatively rigid backing, no allowance or compensation for deformation of the backing is necessary. Polyurethanes and epoxy resin formulations are preferred backing materials for these types of sensors. The variance in capacitance among the various
25 elements of the array, when edge effects are compensated, will then be a direct measure of conformity to the

required shape and size parameters for the object being evaluated. A specific set of tolerances may be developed, either as a lookup table or by a specific algorithm for manipulating the values detected, which can

5 furnish yes or no decisions concerning the acceptability of the object, and additionally, in many operations, to quantify the out of tolerance parameters to serve as control signals for corrective operations.

The secondary dedicated sensor arrays may, as those

10 of ordinary skill in the art will appreciate, be used in conjunction with other types of jigs and tools for the measurement and evaluation of parts.

Since the primary sensor array is most often employed with a robotic gripper or hand, it is relatively

15 simple for the system to transport the object to the secondary sensor, engage the object with the sensor, and then transport the object to the next appropriate location, as determined by the system logic. In an alternative approach, it is also possible to move the

20 sensor to the part by a separate mechanism. It may be necessary for the gripper to release the object while the measurement is made, but that can be an appropriate opportunity for the gripper to then grasp the object in the optimum location and orientation for the next

25 subsequent operations.

It is also possible to use such secondary dedicated sensor arrays for the resolution of part identification ambiguities which cannot be finally resolved by the primary sensor array. By a combination of usage of the

5   primary array for screening, and dedicated shaped arrays for final resolution, a very high reliability in part identification is possible, and the processor computational and data comparison burdens may be materially reduced and spread over time. Since such

10   ambiguities will not often exist for every part engaged, the extra manipulation and processing involved will be an intermittent operation.

If the robot system includes tools for controlled working of the parts, it may be possible to bring each

15   part, or many parts within tolerances by such techniques, employing the data obtained from the dedicated sensor array to guide such corrective work, such as grinding, polishing, and the like. With appropriate means to clean the part, it can be subjected to periodic reevaluation

20   for its conformity to specifications. It may be possible, and in some cases desirable to provide such operations as a branch loop in the robotic operation with separate equipment to permit continuing operation of the primary operations while corrections are being made to

25   out of spec parts.

As those of ordinary skill in the art will have already recognized, the dedicated sensor array operations function as smart feeler gauges, and offer to the art rather precise capabilities to improve quality control of

5   part evaluation, correction and subsequent use in a fashion which offers considerable improvement. Such operations have been largely done by manual operations, requiring highly skilled and expensive labor in relatively large amounts. Hand operations do not offer

10   the level of precision or reliability attainable in the present technique, and are generally slow. The present invention offers relief to the art from the generally slow and unpopular requirements of such operations, with a substantial opportunity for improved results and

15   reduced boredom in the work shop.

The foregoing discussion is illustrative and the specification and drawings are not intended to be limiting on the scope of the present invention. They are intended to guide those of ordinary skill in the art in

20   the practice of the invention, and should not be construed as definitive of the meets and bounds of the invention. The limits of the invention are defined by the following claims:

25

CLAIMS

1.   A capacitance sensor array for proximity and
tactile sensing of properties of an object comprising a
plurality of capacitor plate elements formed in an array
5   of known topology, means for actively connecting each of
said plate elements and said object to one of a plurality
of corresponding oscillator circuits so that the
oscillation frequency of each said circuit is a function
of the capacitance between each said plate element and
10   said object, and means for generating an output from said
sensor which is a function of the tactile properties of
said object from the said plurality of oscillator
circuits.

2.   The sensor of claim 1 wherein said output is a
15   function of slip between said sensor and said object.

3.   The sensor of claim 2 wherein said output is a
function of a relative movement between said sensor and
said object with a lower limit of about 1000 micrometers.

4.   The sensor of claim 2 wherein said output is a
20   function of a relative movement between said sensor and
said object with a lower limit of about 100 micrometers.

5.   The sensor of claim 2 wherein said output is a
function of a relative movement between said sensor and
said object with a lower limit of about 2.5 micrometers.

25   6.   The sensor of claim 2 wherein said output
detects slip in about 50 milliseconds or less.

7. The sensor of claim 2 wherein said output detects slip in about 30 milliseconds or less.

8 The sensor of claim 2 wherein said output detects slip in about 10 milliseconds or less.

9 A capacitance sensor for detecting relative movement between said sensor and an object with a lower limit of about 2.5 micrometers in a time of about 10 milliseconds or less, comprising means for capacitively coupling said sensor and said object, oscillator means having a frequency rate which is a function of the capacitance between said sensor and said object, and means for generating an output signal which is a measure of slip from a change in the frequency of said oscillator representing a change in capacitance between said sensor and said object.

10 The sensor of claim 1 wherein said output is a plurality of signals corresponding to the oscillation frequency of each said oscillator.

11 The sensor of claim 11 wherein said output is a continuous parallel output.

12 The sensor of claim 11 wherein said output is a serial output of each of said plurality of oscillators taken in sequence.

13 The sensor of claim 11 wherein said output is a serial plurality of sequential parallel outputs of a plurality of said oscillators.

14   A detector for determining tactile and proximity information concerning an object, comprising a sensor ... and signal processing means for employing said sensor signals to determine tactile and proximity

5   information about said object.

15   The detector of claim 15 wherein said signal processing means evaluates the change in capacitance between said detector and said object as a function of the distance between them.

10   16   The detector of claim 15 wherein said signal processing means evaluates the capacitance signals to detect the shape of said object.

17   The detector of claim 15 wherein said signal processing means evaluates the capacitance signals to

15   detect the orientation of said object.

18   The detector of claim 15 wherein said signal processing means evaluates the capacitance signals to detect the location and orientation of edges of the object.

20   19   The detector of claim 15 wherein said signal processing means evaluates the capacitance signals to detect a relative movement between the sensor and said object.

25

20 The detector of claim 15 wherein said signal processing means is employed to generate control signals for a tool which is operatively associated with said object.

5   21. The detector of claim 21 wherein said control signals are generated as real time controls of said tool.

22. The detector of claim 21 wherein said control signals are real time closed loop feedback control signals.

10   23. The detector of claim 23 wherein said tool is a robotic gripper which engages and manipulates said object.

24.   A capacitance sensor array for tactile sensing of quality control properties of an

15 object comprising a plurality of capacitor plate elements formed in an array of topology conforming to the topology of the design of said object, means for actively connecting each of said plate elements and said object to one of a plurality of corresponding oscillator circuits

20 so that the oscillation frequency of each said circuit is a function of the capacitance between each said plate element and said object, and means for generating an output from said sensor which is a function of the conformity of the shape of said object to the shape of

25 said design topology of said object determined by response of the said plurality of oscillator circuits.

FIG. 1
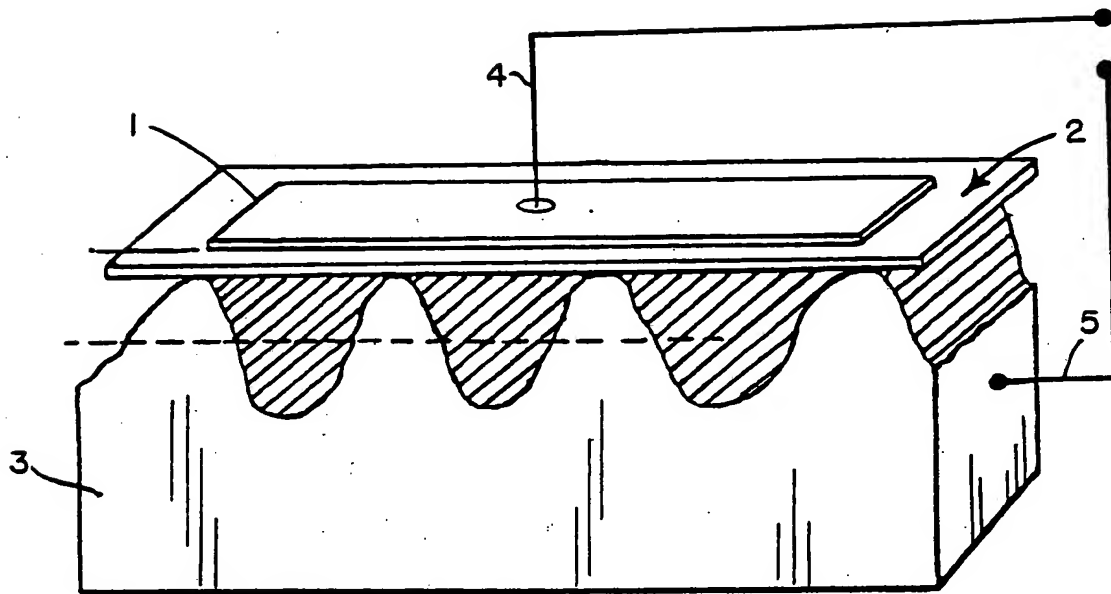
FIG. 2
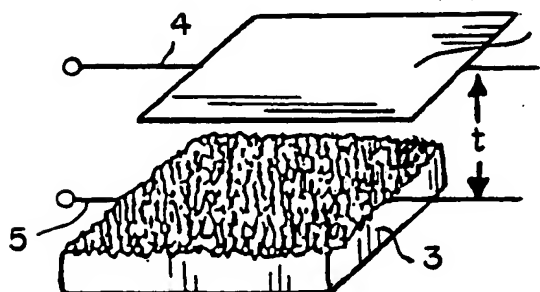
$$C = K \frac{A}{t}$$

SUBSTITUTE SHEET

FIG. 3
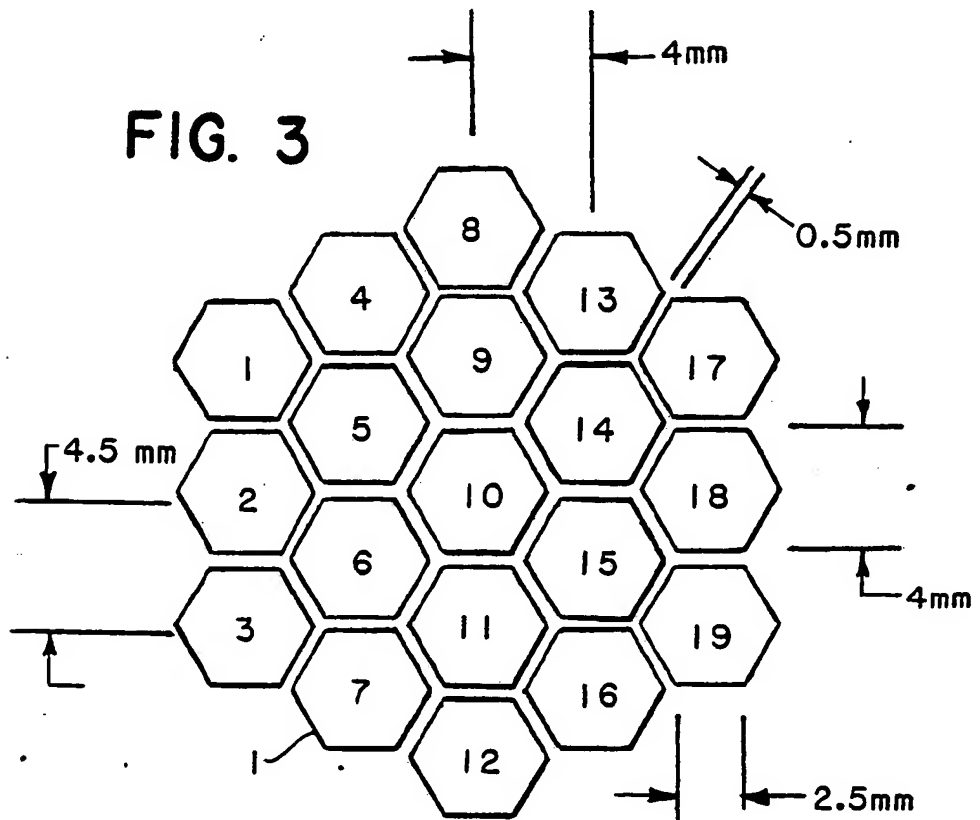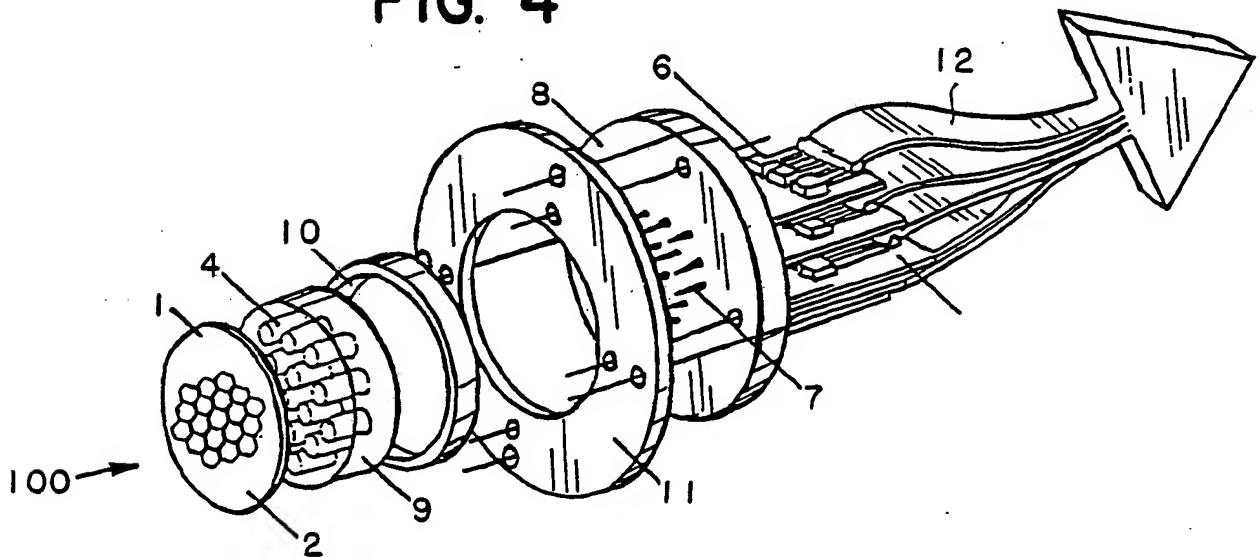
4mm

0.5mm

4.5 mm

4mm

2.5mm

1

8	13	17
4	9	14	18
1	5	10	15	19
2	6	11	16
3	7	12

FIG. 4

100

1
4
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2
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7

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all) 3

According to International Patent Classification (IPC) or to both National Classification and IPC

IPC (4): G01R 27/26
U.S. Cl. 324/61QS

II. FIELDS SEARCHED

Minimum Documentation Searched 4

Classification System	Classification Symbols
U.S.	324/61QS,61QL; 340/870.37; 901/33, 46

Documentation Searched other than Minimum Documentation
to the Extent that such Documents are Included in the Fields Searched 5

III. DOCUMENTS CONSIDERED TO BE RELEVANT 14

Category *	Citation of Document, 16 with indication, where appropriate, of the relevant passages 17	Relevant to Claim No. 18
X	US, A, 4,413,349 (BAILEY) 01 November 1983 See figure 3; column 2 lines 56-58 column 3, lines 38-49	14, 15, 16, 17 18, 19 and 24
Y	US, A, 4,413,349 (BAILEY) 01 November 1983 See the entire document.	1-13
Y,P	US, A, 4,611,296 (NIEDERMAYR 09 September 1986 See claim 15, col. 4, lines 58-66, col. 6, lines 1-15	1-13
Y	US, A, 4,526,043 (BOIE, et al.) 2 July 1985 See col. 1, line 67 - col. 2 line 42; col. 3, lines 20-45 col. 3, line 67 -col. 4, line 2	1-13
Y	US, A, 4,584,625 (KELLOGG) 22 April 1986 See entire document.	1-3, 14-23
X	US, A, 4,557,386 (BUCKLEY, et al) 10 December 1985 See the entire document.	1, 14
A	US, A, 4,588,348 (BENI, et al.) 13 May 1986 See the entire document.	1, 14

* Special categories of cited documents: 16

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

IV. CERTIFICATION

Date of the Actual Completion of the International Search 3	Date of Mailing of this International Search Report 2
23 October 1987	16 NOV 1987
International Searching Authority 1	Signature of Authorized Officer 20
ISA/US	Howard Williams *Howard S Williams*

FURTHER INFORMATION CONTINUED FROM THE SECOND SHEET

A	US, A, 3,651,505 (SCHMIDT) 21 March 1972 See the entire document.	1, 14
A	G.D.R. B, DD 226,827 A1 (HEINZ) 4 September 1985 See the entire document.	1, 14

V.☐ OBSERVATIONS WHERE CERTAIN CLAIMS WERE FOUND UNSEARCHABLE 10

This international search report has not been established in respect of certain claims under Article 17(2) (a) for the following reasons:

1.☐ Claim numbers ...., because they relate to subject matter 12 not required to be searched by this Authority, namely:

2.☐ Claim numbers............, because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out 13, specifically:

VI.☐ OBSERVATIONS WHERE UNITY OF INVENTION IS LACKING 11

This International Searching Authority found multiple inventions in this international application as follows:

1.☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims of the international application.

2.☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims of the international application for which fees were paid, specifically claims:

3.☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claim numbers:

4.☐ As all searchable claims could be searched without effort justifying an additional fee, the International Searching Authority did not invite payment of any additional fee.

Remark on Protest

☐ The additional search fees were accompanied by applicant's protest.

☐ No protest accompanied the payment of additional search fees.